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UTILITY PATENT APPLICATION TRANSMITTAL

Under Small Entity Status

(New Nonprovisional Applications Under 37 CFR § 1.53(b))

Attorney Docket No. 905.01

TO THE ASSISTANT COMMISSIONER FOR PATENTS:

Transmitted herewith is the patent application of ( ) application identifier or (X) first named inventor, Pankaj Topiwala, entitled Fast Lapped Image Transforms Using Lifting Steps, for a(n):

(X) Original Patent Application.
( ) Continuing Application (prior application not abandoned):
( ) Continuation ( ) Divisional ( ) Continuation-in-part (CIP)
of prior Application No. ___________, filed on _______________.
( ) A statement claiming priority under 35 USC § 120 has been added to the specification.

Enclosed are:
(X) Specification; 21 Total Pages. (X) Drawing(s); 5 Total Sheets.
(X) Oath or Declaration:
(X) A Newly Executed Combined Declaration and Power of Attorney:
(X) Signed. ( ) Unsigned. ( ) Partially Signed.
( ) A Copy from a Prior Application for Continuation/Divisional (37 CFR § 1.63(d)).
( ) Incorporation by Reference. The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied, is considered as being part of the disclosure of the accompanying application and is hereby incorporated herein by reference.
( ) Signed Statement Deleting Inventor(s) Named in the Prior Application. (37 CFR § 163(d)(2)).
( ) Power of Attorney. (X) Return Receipt Postcard.
( ) Associate Power of Attorney. (X) A Check in the amount of $_559.00 _for the Filing Fee.
( ) Preliminary Amendment. ( ) Information Disclosure Statement and Form PTO-1449.
( ) A Certified Copy of Priority Documents (if foreign priority is claimed).
(X) Statement(s) of Status as a Small Entity.
( ) Statement(s) of Status as a Small Entity Filed in Prior Application, Status Still Proper and Desired.
( ) Other: ______________________________________.

CLAIMS AS FILED

FOR	NO. FILED	NO. EXTRA	RATE	FEE
Total Claims	15	0	$11.00	$0.00
Independent Claims	7	4	$41.00	$164.00
Multiple Dependent Claim Fee (if applicable)				$0.00
Assignment Recording Fee (if applicable)				$0.00
Basic Filing Fee				$395.00
			Total Filing Fee	$559.00

Please charge $_______ to Deposit Account No. __________ pursuant to 37 CFR § 1.25. At any time during the pendency of this application, the Commissioner is hereby authorized to charge any fees required or credit any overpayment to this Deposit Account. A duplicate copy of this sheet is enclosed for fee processing against this Deposit Account.

Respectfully submitted,

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Attorney Docket No: 905.01

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) AND 1.27(b)) - INDEPENDENT INVENTOR

I hereby declare that I qualify as an independent inventor as defined in 37 CFR 1.9(c) for purposes of paying reduced fees under section 41(a) and (b) of Title 35, United States Code, to the Patent and Trademark Office with regard to the invention entitled:

Fast Lapped Image Transforms Using Lifting Steps

described in (X) the specification filed herewith with title as listed above.
( ) application serial no. __ filed __.
( ) patent no. __ issued __.

I have not assigned, granted, conveyed or licensed and am under no obligation under contract or law to assign, grant, convey, or license, any rights in the invention to any person who could not be classified as an independent inventor under 37 CFR 1.9(c) if that person had made the invention, or to any concern which would not qualify as a small business concern under 37 CFR 1.9(d) or a non-profit organization under 37 CFR 1.9(e).

Each person concern, or organization to which I have assigned, granted, conveyed, or licensed or am under an obligation under contract or law to assign, grant, convey, or license any rights in the invention is listed below:

( ) No such persons, concerns, or organizations exist.
(X) Persons, concerns, or organizations are listed below:

Name FastVideo, ~~Inc.~~ LLC
Address: 10836 Caraway Circle, Manassas, VA 22110

( ) Individual
(X) Small Business Concern
( ) Nonprofit Organization

Name

( ) Individual
( ) Small Business Concern
( ) Nonprofit Organization

Separate verified statements are required from each named person, concern, or organization having rights to the invention averring to their status as small entities. (37 CFR 1.27)

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing from thereon, or any patent to which this verified statement is directed.

Dr. Pankaj Topiwala
NAME OF INVENTOR
Paul Topl
Signature of Inventor
12/13/98
Date

Dr. Trac D. Tran
NAME OF INVENTOR
Trac Tran
Signature of Inventor
12/13/98
Date

Attorney Docket No: 905.01

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) AND 1.27(c)) - SMALL BUSINESS CONCERN

12/11/98 TT 12/13/98

I hereby declare that I am

(X) the owner of the small business concern identified below:
( ) an official of the small business concern empowered to act on behalf of the small business concern identified below:

Name of Small Business Concern: FastVideo, ~~Inc.~~ LLC
Address of Small Business Concern: 10836 Caraway Drive
Manassas, VA 22110

I hereby declare that the above identified concern qualifies as a small business concern as defined in 13 CFR 121.1301 through 121.1305, and reproduced in 37 CFR 1.9(d), for purposes of paying reduced fees under section 41(a) and (b) of Title 35, United States Code, in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time, or temporary basis during each of the pay periods of the fiscal year, and (2) concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third party or parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to and remain with the small business concern identified above with regard to the invention, entitled Fast Lapped Image Transforms Using Lifting Steps, by inventor(s) Pankaj Topiwala and Trac D. Tran,

described in (X) the specification filed herewith with title as listed above.
( ) application serial no. filed .
( ) patent no. __ issued __.

If the rights held by the above identified small business concern are not exclusive, each individual, concern, or organization having rights to the invention is listed below and no rights to the invention are held by any person, other than the inventor, who could not qualify as an independent inventor under 37 CFR 1.9(c) if that person made the invention, or by any concern which would not qualify as a small business concern under 37 CFR 1.9(d), or a nonprofit organization under 37 CFR 1.9(e).

(X) No such persons, concerns, or organizations exist.
( ) Persons, concerns, or organizations are listed below:

Name ____________	Name ____________
Address ____________	Address ____________
( ) Individual	( ) Individual
( ) Small Business Concern	( ) Small Business Concern
( ) Nonprofit Organization	( ) Nonprofit Organization

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING Pankaj Topiwala

TITLE OF PERSON IF OTHER THAN OWNER President & CEO

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SIGNATURE ______________ DATE 12/11/98

TRAN & TOPIWALA, ATTORNEY DOCKET NO. 905.01

Application For United States Patent For

FAST LAPPED IMAGE TRANSFORMS USING LIFTING STEPS

Trac D. Tran
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and

Pankaj Topiwala,
Manassas, Virginia

FIELD OF THE INVENTION

The current invention relates to the processing of images such as photographs, drawings, and other two dimensional displays. It further relates to the processing of such images which are captured in digital format or after they have been converted to or expressed in digital format. This invention further relates to use of novel coding methods to increase the speed and compression ratio for digital image storage and transmission while avoiding introduction of undesirable artifacts into the reconstructed images.

BACKGROUND OF THE INVENTION

In general, image processing is the analysis and manipulation of two-dimensional representations, which can comprise photographs, drawings, paintings, blueprints, x-rays of medical patients, or indeed abstract art or artistic patterns. These images are all two-dimensional arrays of information. Until fairly recently, images have comprised almost exclusively analog displays of analog information, for example, conventional photographs and motion pictures. Even the signals encoding television pictures, notwithstanding that the vertical scan comprises a finite number of lines, are fundamentally analog in nature.

Beginning in the early 1960's, images began to be captured or converted and stored as two-dimensional digital data, and digital image processing followed. At first, images were recorded or transmitted in analog form and then converted to digital representation for manipulation on a computer. Currently digital capture and transmission are on their way to dominance, in part because of the advent of charge coupled device (CCD) image recording arrays and in part because of the availability of inexpensive high speed computers to store and manipulate images.

An important task of image processing is the correction or enhancement of a particular image. For example, digital enhancement of images of celestial objects taken by space probes has provided substantial scientific information. However, the current invention relates primarily to compression for transmission or storage of digital images and not to enhancement.

One of the problems with digital images is that a complete single image frame can

require up to several megabytes of storage space or transmission bandwidth. That is, one of today's 3-1/2 inch floppy discs can hold at best a little more than one gray-scale frame and sometimes substantially less than one whole frame. A full-page color picture, for example, uncompressed, can occupy 30 megabytes of storage space. Storing or transmitting the vast amounts of data which would be required for real-time uncompressed high resolution digital video is technologically daunting and virtually impossible for many important communication channels, such as the telephone line. The transmission of digital images from space probes can take many hours or even days if insufficiently compressed images are involved. Accordingly, there has been a decades long effort to develop methods of extracting from images the information essential to an aesthetically pleasing or scientifically useful picture without degrading the image quality too much and especially without introducing unsightly or confusing artifacts into the image.

The basic approach has usually involved some form of coding of picture intensities coupled with quantization. One approach is block coding; another approach, mathematically equivalent with proper phasing, is multiphase filter banks. Frequency based multi-band transforms have long found application in image coding. For instance, the JPEG image compression standard, W. B. Pennebaker and J. L. Mitchell, "JPEG: Still Image Compression Standard," Van Nostrand Reinhold, 1993, employs the 8 x 8 discrete cosine transform (DCT) at its transformation stage. At high bit rates, JPEG offers almost lossless reconstructed image quality. However, when more compression is needed, annoying blocking artifacts appear since the DCT bases are short and do not overlap, creating discontinuities at block boundaries.

The wavelet transform, on the other hand, with long, varying-length, and overlapping bases, has elegantly solved the blocking problem. However, the transform's computational complexity can be significantly higher than that of the DCT. This complexity gap is partly in terms of the number of arithmetical operations involved, but more importantly, in terms of the memory buffer space required. In particular, some implementations of the wavelet transform require many more operations per output coefficient as well as a large buffer.

An interesting alternative to wavelets is the lapped transform, e.g., H. S. Malvar, Signal Processing with Lapped Transforms, Artech House, 1992, where pixels from adjacent

blocks are utilized in the calculation of transform coefficients for the working block. The lapped transforms outperform the DCT on two counts: (i) from the analysis viewpoint, they take into account inter-block correlation and hence provide better energy compaction; (ii) from the synthesis viewpoint, their overlapping basis functions decay asymptotically to zero at the ends, reducing blocking discontinuities dramatically.

Nevertheless, lapped transforms have not yet been able to supplant the unadorned DCT in international standard coding routines. The principal reason is that the modest improvement in coding performance available up to now has not been sufficient to justify the significant increase in computational complexity. In the prior art, therefore, lapped transforms remained too computationally complex for the benefits they provided. In particular, the previous lapped transformed somewhat reduced but did not eliminate the annoying blocking artifacts.

It is therefore an object of the current invention to provide a new transform which is simple and fast enough to replace the bare DCT in international standards, in particular in JPEG and MPEG-like coding standards. It is another object of this invention to provide an image transform which has overlapping basis functions so as to avoid blocking artifacts. It is a further object of this invention to provide a lapped transform which is approximately as fast as, but more efficient for compression than, the bare DCT. It is yet another object of this invention to provide dramatically improved speed and efficiency using a lapped transform with lifting steps in a butterfly structure with dyadic-rational coefficients. It is yet a further object of this invention to provide a transform structure such that for a negligible complexity surplus over the bare DCT a dramatic coding performance gain can be obtained both from a subjective and objective point of view while blocking artifacts are completely eliminated.

SUMMARY OF THE INVENTION

In the current invention, we use a family of lapped biorthogonal transforms implementing a small number of dyadic-rational lifting steps. The resulting transform, called the LiftLT, not only has high computation speed but is well-suited to implementation via VLSI. Moreover, it also consistently outperforms state-of-the-art wavelet based coding systems in

coding performance when the same quantizer and entropy coder are used. The LiftLT is a lapped biorthogonal transform using lifting steps in a modular lattice structure, the result of which is a fast, efficient, and robust encoding system. With only 1 more multiplication (which can also be implemented with shift-and-add operations), 22 more additions, and 4 more delay elements compared to the bare DCT, the LiftLT offers a fast, low-cost approach capable of straightforward VLSI implementation while providing reconstructed images which are high in quality, both objectively and subjectively. Despite its simplicity, the LiftLT provides a significant improvement in reconstructed image quality over the traditional DCT in that blocking is completely eliminated while at medium and high compression ratios ringing artifacts are reasonably contained. The performance of the LiftLT surpasses even that of the well-known 9/7-tap biorthogonal wavelet transform with irrational coefficients. The LiftLT's block-based structure also provides several other advantages: supporting parallel processing mode, facilitating region-of-interest coding and decoding, and processing large images under severe memory constraints.

Most generally, the current invention is an apparatus for block coding of windows of digitally represented images comprising a chain of lattices of lapped transforms with dyadic rational lifting steps. More particularly, this invention is a system of electronic devices which codes, stores or transmits, and decodes M x M sized blocks of digitally represented images, where M is ~~a power of 2~~ an even number. The main block transform structure comprises a transform having M channels numbered 0 through M-1, half of said channel numbers being odd and half being even; a normalizer with a dyadic rational normalization factor in each of said M channels; two lifting steps with a first set of identical dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration; M/2 delay lines in the odd numbered channels; two inverse lifting steps with the first set of dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration; and two lifting steps with a second set of identical dyadic rational coefficients connecting each pair of adjacent odd numbered channels; means for transmission or storage of the transform output coefficients; and an inverse transform comprising M channels numbered 0 through M-1, half of said channel numbers being odd and half being even; two inverse lifting steps with dyadic rational coefficients connecting each pair of adjacent odd

numbered channels; two lifting steps with dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration; M/2 delay lines in the even numbered channels; two inverse lifting steps with dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration; a denormalizer with a dyadic rational inverse normalization factor in each of said M channels; and a base inverse transform having M channels numbered 0 through M-1.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a polyphase representation of a linear phase perfect reconstruction filter bank.

Figure 2 shows the most general lattice structure for linear phase lapped transforms with filter length $L = KM$.

Figure 3 shows the parameterization of an invertible matrix via the singular value decomposition.

Figure 4 portrays the basic butterfly lifting configuration.

Figure 5 depicts the analysis LiftLT lattice drawn for $M = 8$.

Figure 6 depicts the synthesis LiftLT lattice drawn for $M = 8$.

Figure 7 depicts a VLSI implementation of the analysis filter bank operations.

Figure 8 shows frequency and time responses of the *8x16* LiftLT: Left: analysis bank. Right: synthesis bank.

Figure 9 portrays reconstructed "Barbara" images at 1:32 compression ratio.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Typically, a block transform for image processing is applied to a block (or window) of, for example, 8 x 8 group of pixels and the process is iterated over the entire image. A biorthogonal transform in a block coder uses as a decomposition basis a complete set of basis vectors, similar to an orthogonal basis. However, the basis vectors are more general in that they may not be orthogonal to all other basis vectors. The restriction is that there is a "dual" basis to the original biorthogonal basis such that every vector in the original basis has a "dual" vector in the dual basis to which it is orthogonal. The basic idea of combining the concepts of biorthogonality and lapped transforms has already appeared in the prior art. The most general lattice for M-channel linear phase lapped biorthogonal transforms is presented in T. D. Tran, R. de Queiroz, and T. Q. Nguyen, "The generalized lapped biorthogonal transform," ICASSP, pp. 1441-1444, Seattle, May 1998, and in T. D. Tran, R. L. de Queiroz, and T. Q. Nguyen, "Linear phase perfect reconstruction filter bank: lattice structure, design, and application in image coding" (submitted to IEEE Trans. on Signal Processing, Apr. 1998). A signal processing flow diagram of this well-known generalized filter bank is shown in Fig. 2.

In the current invention, which we call the Fast LiftLT, we apply lapped transforms based on using fast lifting steps in an M-channel uniform linear-phase perfect reconstruction filter bank, according to the generic polyphase representation of Figure 1. In the lapped biorthogonal approach, the polyphase matrix $E(z)$ can be factorized as

$$\mathbf{E(z)} = \mathbf{G}_{K-1}(\mathbf{z})\mathbf{G}_{K-2}(\mathbf{z})\cdots\mathbf{G}_1(\mathbf{z})\mathbf{E}_0(\mathbf{z}), \quad \text{where} \qquad (1)$$

$$\mathbf{G}_i(\mathbf{z}) = \frac{1}{2}\begin{bmatrix}\mathbf{U}_i & \mathbf{0}\\ \mathbf{0} & \mathbf{V}_i\end{bmatrix}\begin{bmatrix}\mathbf{I} & \mathbf{I}\\ \mathbf{I} & -\mathbf{I}\end{bmatrix}\begin{bmatrix}\mathbf{I} & \mathbf{0}\\ \mathbf{0} & \mathbf{z}^{-1}\mathbf{I}\end{bmatrix}\begin{bmatrix}\mathbf{I} & \mathbf{I}\\ \mathbf{I} & -\mathbf{I}\end{bmatrix} \equiv \frac{1}{2}\ \Phi_i \times \mathbf{W} \times \Lambda(\mathbf{z}) \times \mathbf{W}, \ \text{and} \qquad (2)$$

$$\mathbf{E}_0(\mathbf{z}) = \frac{1}{\sqrt{2}}\begin{bmatrix}\mathbf{U}_0 & \mathbf{U}_0\mathbf{J}_{M/2}\\ \mathbf{V}_0\mathbf{J}_{M/2} & -\mathbf{V}_0\end{bmatrix}. \qquad (3)$$

PT 12/13/98
TT 12/13/98

In these equations, **I** is the identity matrix, and J is ~~th~~ matrix with 1's on the anti-diagonal.

The transform decomposition expressed by equations (1) through (3) is readily represented, as shown in Figure 2, as a complete lattice replacing the "analysis" filter bank **E(z)** of

PT 12/13/98 TT 12/13/99

Figure 1. This decomposition results in a lattice of filters having length $L = KM$. (K is often called the overlapping factor.) Each cascading structure $\mathbf{G}_i(z)$ increases the filter length by M. All $\mathbf{U}_i$ and $\mathbf{V}_i$, $i = 0, 1, \cdots, K-1$, are arbitrary $M/2 \times M/2$ invertible matrices. According to a theorem well known in the art, invertible matrices can be completely represented by their singular value decomposition (SVD), given by

$$\mathbf{U}_i = \mathbf{U}_{i0}\,\Gamma_i\,\mathbf{U}_{i1}, \quad \mathbf{V}_i = \mathbf{V}_{i0}\,\Delta_i\,\mathbf{V}_{i1}$$

where $\mathbf{U}_{i0}, \mathbf{U}_{i1}, \mathbf{V}_{i0}, \mathbf{V}_{i1}$ are diagonalizing orthogonal matrices and Γ_i, Δ_i are diagonal matrices with positive elements.

It is well known that any $M/2 \times M/2$ orthogonal matrix can be factorized into $M(M-2)/8$ plane rotations θ_i and that the diagonal matrices represent simply scaling factors α_i. Accordingly, the most general LT lattice consists of $KM(M-2)/2$ two dimensional rotations and $2M$ diagonal scaling factors α_i. Any invertible ~~The orthogonal~~ matrix can be expressed as a sequence of pairwise plane rotations θ_i and scaling factors α_i as shown in Fig. 3.

PT 12/13/98 TT 12/13/99

It is also well known that a plane rotation can be performed by 3 "shears":

$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} = \begin{bmatrix} 1 & \dfrac{\cos\theta_i - 1}{\sin\theta_i} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \sin\theta_i & 1 \end{bmatrix} \begin{bmatrix} 1 & \dfrac{\cos\theta_i - 1}{\sin\theta_i} \\ 0 & 1 \end{bmatrix}.$$

This can be easily verified by computation. Each of the factors above is an example of a "lifting" step in signal processing terminology. The product of two of which

~~In signal processing terminology, a "lifting" step is one which~~ effects a linear transform of pairs of coefficients:

PT 12/13/98 TT 12/13/99

$$\begin{bmatrix} a \\ b \end{bmatrix} \rightarrow \begin{bmatrix} 1+km & k \\ m & 1 \end{bmatrix} \times \begin{bmatrix} a \\ b \end{bmatrix}.$$

The signal processing flow diagram of this operation is shown in Fig. 4. The crossing arrangement of these flow paths is also referred to as a butterfly configuration. Each of the above "shears" can be written as a lifting step.

Combining the foregoing, the shears referred to can be expressed as

computationally equivalent "lifting steps" in signal processing. In other words, we can replace each "rotation" by 3 closely-related lifting steps with butterfly structure. It is possible therefore to implement the complete LT lattice shown in Figure 2 by *3KM(M-2)/2* lifting steps and *2M* scaling multipliers.

In the simplest but currently preferred embodiment, to minimize the complexity of the transform we choose a small overlapping factor K=2 and set the initial stage $\mathbf{E}_0$ to be the DCT itself. Many other coding transforms can serve for the base stage instead of the DCT, and it should be recognized that many other embodiments are possible and can be implemented by one skilled in the art of signal processing.

Following the observation in H. S. Malvar, "Lapped biorthogonal transforms for transform coding with reduced blocking and ringing artifacts," ICASSP97, Munich, April 1997, we apply a scaling factor to the first DCT's antisymmetric basis to generate synthesis LT basis functions whose end values decay smoothly to exact zero -- a crucial advantage in blocking artifacts elimination. However, instead of scaling the analysis by $\sqrt{2}$ and the synthesis by $1/\sqrt{2}$, we opt for *25/16* and its inverse *16/25* since they allow the implementation of both analysis and synthesis banks in integer arithmetic. Another value that works almost as well as *25/16* is *5/4*. To summarize, the following choices are made in the first stage: the combination of $\mathbf{U}_{00}$ and $\mathbf{V}_{00}$ with the previous butterfly form the DCT; $\mathbf{\Delta}_0 = diag[\frac{25}{16},1,\cdots,1]$, and $\mathbf{\Gamma}_0 = \mathbf{U}_{00} = \mathbf{V}_{00} = \mathbf{I}_{M/2}$. See Fig. 2.

After 2 series of ± 1 butterflies $\mathbf{W}$ and the delay chain $\Lambda(z)$, the LT symmetric basis functions already have good attenuation, especially at DC ($\omega = 0$). Hence, we can comfortably set $\mathrm{U}_1 = \mathrm{I}_{M/2}$.

As noted, V_1 is factorizable into a series of lifting steps and diagonal scalings. However, there are several problems: (i) the large number of lifting steps is costly in both speed and physical real-estate in VLSI implementation; (ii) the lifting steps are related; (iii) and it is not immediately obvious what choices of rotation angles will result in dyadic rational lifting multipliers. In the current invention, we approximate V_1 by (M/2) - 1 combinations of block-

diagonal predict-and-update lifting steps, i.e.,

$$\begin{bmatrix} 1 & u_i \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ -p_i & 1 \end{bmatrix}.$$

Here, the free parameters u_i and p_i can be chosen arbitrarily and independently without affecting perfect reconstruction. The inverses are trivially obtained by switching the order and the sign of the lifting steps. Unlike popular lifting implementations of various wavelets, all of our lifting steps are of zero-order, namely operating in the same time epoch. In other words, we simply use a series of *2x2* upper or lower diagonal matrices to parameterize the invertible matrix V_1.

Most importantly, fast-computable VLSI-friendly transforms are readily available when u_i and p_i are restricted to dyadic rational values, that is, rational fractions having (preferably small) powers of 2 denominators. With such coefficients, transform operations can for the most part be reduced to a small number of shifts and adds. In particular, setting all of the approximating lifting step coefficients to *–1/2* yields a very fast and elegant lapped transform. With this choice, each lifting step can be implemented using only one simple bit shift and one addition.

The resulting LiftLT lattice structures are presented in Figures 5 and 6. The analysis filter shown in Fig. 5 comprises a DCT block **1**, 25/16 normalization **2**, a delay line **3** on four of the eight channels, a butterfly structured set of lifting steps **5**, and a set of four fast dyadic lifting steps **6**. The frequency and impulse responses of the *8x16* LiftLT's basis functions are depicted in Figure 8.

The inverse or synthesis lattice is shown in Fig. 6. This system comprises a set of four fast dyadic lifting steps **11**, a butterfly-structured set of lifting steps **12**, a delay line **13** on four of the eight channels, 16/25 inverse normalization **14**, and an inverse DCT block **15**. Fig. 7 also shows the frequency and impulse responses of the synthesis lattice.

The LiftLT is sufficiently fast for many applications, especially in hardware, since most of the incrementally added computation comes from the 2 butterflies and the *6* shift-and-add lifting steps. It is faster than the type-I fast LOT described in H. S. Malvar, *Signal Processing*

with Lapped Transforms, Artech House, 1992. Besides its low complexity, the LiftLT possesses many characteristics of a high-performance transform in image compression: (i) it has high energy compaction due to a high coding gain and a low attenuation near DC where most of the image energy is concentrated; (ii) its synthesis basis functions also decay smoothly to zero, resulting in blocking-free reconstructed images.

Comparisons of complexity and performance between the LiftLT and other popular transforms are tabulated in Table 1 and Table 2. The LiftLT's performance is already very close to that of the optimal generalized lapped biorthogonal transform, while its complexity is the lowest amongst the transforms except for the DCT.

To assess the new method in image coding, we compared images coded and decoded with four different transforms:

DCT: *8*-channel, *8*-tap filters

Type-I Fast LOT: *8*-channel, *16*-tap filters

LiftLT: *8*-channel, *16*-tap filters

Wavelet: *9/7*-tap biorthogonal.

In this comparison, we use the same SPIHT's quantizer and entropy coder, A. Said and W. A. Pearlman, "A new fast and efficient image coder based on set partitioning in hierarchical trees," *IEEE Trans on Circuits Syst. Video Tech.*, vol. 6, pp. 243-250, June 1996, for every transform. In the block-transform cases, we use the modified zero-tree structure in T. D. Tran and T. Q. Nguyen, "A lapped transform embedded image coder," *ISCAS*, Monterey, May 1998, where each block of transform coefficients is treated analogously to a full wavelet tree and three more levels of decomposition are employed to decorrelate the DC subband further.

Table 1 contains a comparison of the complexity of these four coding systems, comparing numbers of operations needed per 8 transform coefficients:

Transform	No. Multiplications	No. Additions	No. Shifts
8x8 DCT	13	29	0
8x16 Type-I Fast LOT	22	54	0
9/7 Wavelet, 1-level	36	56	0
8x16 Fast LiftLT	14	51	6

In such a comparison, the number of multiplication operations dominates the "cost" of the transform in terms of computing resources and time, and number of additions and number of shifts have negligible effect. In this table, it is clear that the fast LiftLT is almost as low as the DCT in complexity and more than twice as efficient as the wavelet transform.

Table 2 sets forth a number of different performance measures for each of the four coding methods:

Transform	Coding Gain (dB)	DC Atten. (-dB)	Stopband Atten. (-dB)	Mir. Freq. Atten. (-dB)
8x8 DCT	8.83	310.62	9.96	322.1
8x16 Type-I Fast LOT	9.2	309.04	17.32	314.7
8x16 optimal LT ~~9/7 Wavelet 5-level~~	~~9.62~~	~~327.4~~	~~13.5~~	~~55.54~~
8x16 Fast LiftLT	9.54	312.56	13.21	304.85

Keep #'s !!

PT 12/11/98 TT 12/11/98

The fast LiftLT is comparable to the ~~wavelet~~ optimal 8x16 LT transform in coding gain and stopband attenuation and significantly better than the DCT. ~~in mirror frequency attenuation (a figure of merit related to aliasing)~~.

PT 12/11/98 TT 12/11/98

PT 12/11/98 TT 12/11/98

Reconstructed images for a standard *512x512* "Barbara" test image at 1:32 compression ratio are shown in Figure 9 for aesthetic and heuristic evaluation. Top left **21** is the reconstructed image for the 8 x 8 DCT (27.28 dB PSNR); top right shows the result for the 8 x 16 LOT (28.71 dB PSNR); bottom left is the 9/7 tap wavelet reconstruction (27.58 dB PSNR); and bottom right, 8 x 16 LiftLT (28.93 dB PSNR). The objective coding results for standard *512x512* "Lena," "Goldhill," and "Barbara" test image (PSNR in dB's) are tabulated in Table 3:

	Lena				*Goldhill*				*Barbara*			
Comp. Ratio	9/7 WL SPIHT	8X8 DCT	8X16 LOT	8X16 LiftLT	9/7 WL SPIHT	8X8 DCT	8X16 LOT	8X16 LiftLT	9/7 WL SPIHT	8X8 DCT	8X16 LOT	8X16 LiftLT
8	40.41	39.91	40.02	40.21	36.55	36.25	36.56	36.56	36.41	36.31	37.22	37.57
16	37.21	36.38	36.69	37.11	33.13	32.76	33.12	33.22	31.4	31.11	32.52	32.82
32	34.11	32.9	33.49	34	30.56	30.07	30.52	30.63	27.58	27.28	28.71	28.93
64	31.1	29.67	30.43	30.9	28.48	27.93	28.34	28.54	24.86	24.58	25.66	25.93
100	29.35	27.8	28.59	29.03	27.38	26.65	27.08	27.28	23.76	23.42	24.32	24.5
128	28.38	26.91	27.6	28.12	26.73	26.01	26.46	26.7	23.35	22.68	23.36	23.47

PSNR is an acronym for power signal to noise ratio and represents the logarithm of the ratio of

maximum amplitude squared to the mean square error of the reconstructed signal expressed in decibels (dB).

The LiftLT outperforms its block transform relatives for all test images at all bit rates. Comparing to the wavelet transform, the LiftLT is quite competitive on smooth images -- about 0.2 dB below on Lena. However, for more complex images such as Goldhill or Barbara, the LiftLT consistently surpasses the 9/7-tap wavelet. The PSNR improvement can reach as high as 1.5 dB.

Figure 9 also shows pictorially the reconstruction performance in Barbara images at 1:32 compression ratio for heuristic comparison. The visual quality of the LiftLT reconstructed image is noticeably superior. Blocking is completely avoided whereas ringing is reasonably contained. Top left: 8x8 DCT, 27.28 dB. Top right: 8x16 LOT, 28.71 dB. Bottom left: 9/7-tap wavelet, 27.58 dB. Bottom right: 8x16 LiftLT, 28.93 dB. Visual inspection indicates that the LiftLT coder gives at least as good performance as the wavelet coder. The appearance of blocking artifacts in the DCT reconstruction (upper left) is readily apparent. The LOT transform result (upper right) suffers visibly from the same artifacts even though it is lapped. In addition, it is substantially more complex and therefore slower than the DCT transform. The wavelet transform reconstruction (lower left) shows no blocking and is of generally high quality for this level of compression. It is faster than the LOT but significantly slower than the DCT. Finally, the results of the LiftLT transform are shown at lower right. Again, it shows no blocking artifacts, and the picture quality is in general comparable to that of the wavelet transform reconstruction, while its speed is very close to that of the bare DCT.

CLAIMS

We claim:

1. An apparatus for block coding of windows of digitally represented images comprising a chain of lattices of lapped transforms with dyadic rational lifting steps.

2. An apparatus for coding, storing or transmitting, and decoding M x M sized blocks of digitally represented images, where M is ~~a power of 2~~ an even number, comprising PT 12/21/98 TT 12/17/98

   a. a forward transform comprising

      i. a base transform having M channels numbered 0 through M-1, half of said channel numbers being odd and half being even;

      ii. an equal normalization factor in each of the M channels selected to be dyadic-rational;

      iii. a full-scale butterfly implemented as a series of lifting steps with a first set of dyadic rational coefficients;

      iv. M/2 delay lines in the odd numbered channels;

      v. a full-scale butterfly implemented as a series of lifting steps with said first set of dyadic rational coefficients; and

      vi. a series of lifting steps in the odd numbered channels with a second specifically selected set of dyadic-rational coefficients;

   b. means for transmission or storage of the transform output coefficients; and

   c. an inverse transform comprising

i. M channels numbered 0 through M-1, half of said channel numbers being odd and half being even;

ii. a series of inverse lifting steps in the odd numbered channels with said second set of specifically selected dyadic-rational coefficients;

iii. a full-scale butterfly implemented as a series of lifting steps with said first set of specifically selected dyadic-rational coefficients;

iv. M/2 delay lines in the even numbered channels;

v. a full-scale butterfly implemented as a series of lifting steps with said first set of specifically selected dyadic-rational coefficients;

vi. an equal denormalization factor in each of the M channels specifically selected to be dyadic-rational; and

vii. a base inverse transform having M channels numbered 0 through M-1.

3. The apparatus of Claim 2 in which the normalizing factor takes the value 25/16 and simultaneously the denormalizing factor takes the value 16/25.

4. The apparatus of Claim 2 in which the normalizing factor takes the value 5/4 and simultaneously the denormalizing factor takes the value 4/5.

5. The apparatus of Claim 2 in which the first set of dyadic rational coefficients are all equal to 1.

6. The apparatus of Claim 2 in which the second set of dyadic rational coefficients are all equal to ½.

7. The apparatus of Claim 2 in which the base transform is any M x M invertible matrix of the

form of a linear phase filter and the inverse base transform is the inverse of said M x M invertible matrix.

8. The apparatus of Claim 2 in which the base transform is the forward M x M discrete cosine transform and the inverse base transform is the inverse M x M discrete cosine transform.

9. An apparatus for transforming M x M blocks of digital image intensities comprising lapped transforms with overlapping factor K and having butterfly structures and lifting steps to generate M-channel uniform linear phase perfect reconstruction filter banks.

10. The apparatus of Claim 9 in which K equals 2.

11. An apparatus for coding, compressing, storing or transmitting, and decoding a block of M x M intensities from a digital image selected by an M x M window moving recursively over the image, comprising:

a. an M x M block transform comprising:

i. an initial stage

ii. a normalizing factor in each channel

b. a cascade comprising a plurality of dyadic rational lifting transforms, each of said plurality of dyadic rational lifting transforms comprising

i. a first bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

ii. a bank of delay lines in a first group of M/2 alternating lines;

iii. a second bank of butterfly lifting steps with unitary coefficients, and

iv. a bank of pairs of butterfly lifting steps with coefficients of 1/2 between M/2 -1 pairs of said M/2 alternating lines;

c. means for transmission or storage of the output coefficients of said M x M block transform; and

d. an inverse transform comprising

i. a cascade comprising a plurality of dyadic rational lifting transforms, each of said plurality of dyadic rational lifting transforms comprising

a) a bank of pairs of butterfly lifting steps with coefficients of 1/2 between said M/2 -1 pairs of said M/2 alternating lines;

b) a first bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

c) a bank of delay lines in a second group of M/2 alternating lines; and

d) a second bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

ii. a de-scaling bank; and

iii. an inverse initial stage.

12. A method of block coding windows of digitally represented images comprising successive steps of processing the output of each step through a following step in a chain of lattices of lapped transforms with dyadic rational lifting steps.

PT 12/13/98 TT 12/13/98

13. A method of coding, storing or transmitting, and decoding M x M sized blocks of digitally represented images, where M is ~~a power of 2~~ an even number, comprising

a. transmitting the original picture signals to a coder, which effects the steps of

   i. converting the signals with a base transform having M channels numbered 0 through M-1, half of said channel numbers being odd and half being even;

   ii. normalizing the output of the preceding step with a dyadic rational normalization factor in each of said M channels;

   iii. processing the output of the preceding step through two lifting steps with a first set of identical dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration;

   iv. transmitting the resulting coefficients through M/2 delay lines in the odd numbered channels;

   v. processing the output of the preceding step through two inverse lifting steps with the first set of dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration; and

   vi. applying two lifting steps with a second set of identical dyadic rational coefficients connecting each pair of adjacent odd numbered channels to the output of the preceding step;

b. transmitting or storing the transform output coefficients;

c. receiving the transform output coefficients in a decoder; and

d. processing the output coefficients in a decoder, comprising the steps of

i. receiving the coefficients in M channels numbered 0 through M-1, half of said channel numbers being odd and half being even;

ii. applying two inverse lifting steps with dyadic rational coefficients connecting each pair of adjacent odd numbered channels;

iii. applying two lifting steps with dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration;

iv. transmitting the result of the preceding step through M/2 delay lines in the even numbered channels;

v. applying two inverse lifting steps with dyadic rational coefficients connecting each pair of adjacent numbered channels in a butterfly configuration;

vi. denormalizing the result of the preceding step with a dyadic rational inverse normalization factor in each of said M channels; and

vii. processing the result of the preceding step through a base inverse transform having M channels numbered 0 through M-1.

14. A method of coding, compressing, storing or transmitting, and decoding a block of M x M intensities from a digital image selected by an M x M window moving recursively over the image, comprising the steps of:

a. Processing the intensities in an M x M block coder comprising the steps of:

i. processing the intensities through an initial stage;

ii. scaling the result of the preceding step in each channel;

b. processing the result of the preceding step through a cascade comprising a plurality of

dyadic rational lifting transforms, each of said plurality of dyadic rational lifting transforms comprising

i. a first bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

ii. a bank of delay lines in a first group of M/2 alternating lines;

iii. a second bank of butterfly lifting steps with unitary coefficients, and

iv. a bank of pairs of butterfly lifting steps with coefficients of 1/2 between M/2 -1 pairs of said M/2 alternating lines;

c. transmitting or storing the output coefficients of said M x M block coder;

d. receiving the output coefficients in a decoder; and

e. processing the output coefficients in the decoder, comprising the steps of

i. processing the output coefficients through a cascade comprising a plurality of dyadic rational lifting transforms, each of said plurality of dyadic rational lifting transforms comprising

a) a bank of pairs of butterfly lifting steps with coefficients of 1/2 between said M/2 -1 pairs of said M/2 alternating lines;

b) a first bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

c) a bank of delay lines in a second group of M/2 alternating lines;

d) a second bank of pairs of butterfly lifting steps with unitary coefficients between adjacent lines of said transform;

e) a de-scaling bank; and

f. processing the results of the preceding step in an inverse initial stage.

15. The apparatus of Claim 2, with any approximation of the special constants in this patent filing.

PT 12/13/98
TT 12/13/98

ABSTRACT

This invention introduces a class of multi-band linear phase lapped biorthogonal transforms with fast, VLSI-friendly implementations via lifting steps called the LiftLT. The transform is based on a lattice structure which robustly enforces both linear phase and perfect reconstruction properties. The lattice coefficients are parameterized as a series of lifting steps, providing fast, efficient in-place computation of the transform coefficients as well as the ability to map integers to integers. Our main motivation of the new transform is its application in image and video coding. Comparing to the popular 8×8 DCT, the 8×16 LiftLT only requires 1 more multiplication, 22 more additions, and 6 more shifting operations. However, image coding examples show that the LiftLT is far superior to the DCT in both objective and subjective coding performance. Thanks to properly designed overlapping basis functions, the LiftLT can completely eliminate annoying blocking artifacts. In fact, the novel LiftLT's coding performance consistently surpasses that of the much more complex 9/7-tap biorthogonal wavelet with floating-point coefficients. More importantly, our transform's block-based nature facilitates one-pass sequential block coding, region-of-interest coding/decoding as well as parallel processing.

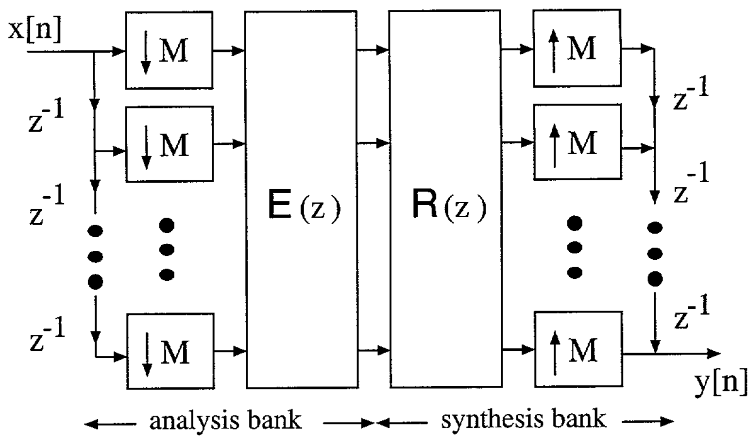

Figure 1

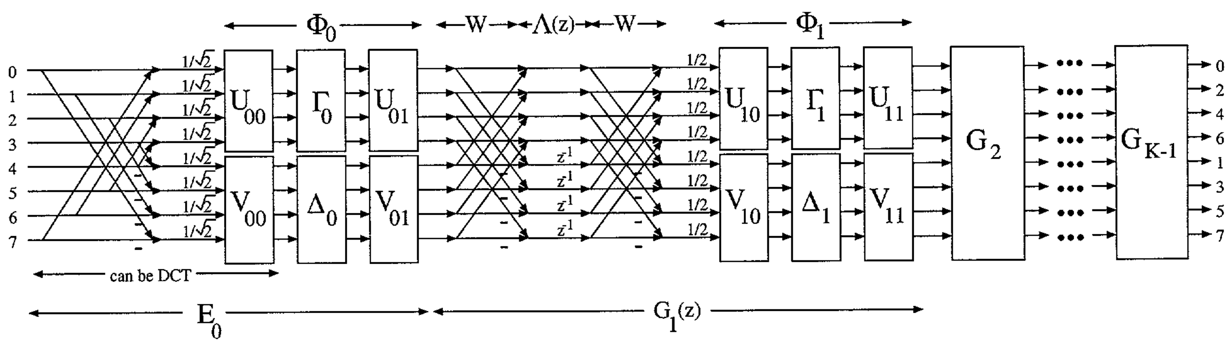

Figure 2

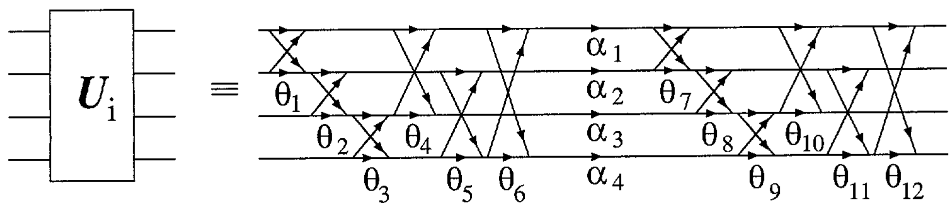

Figure 3

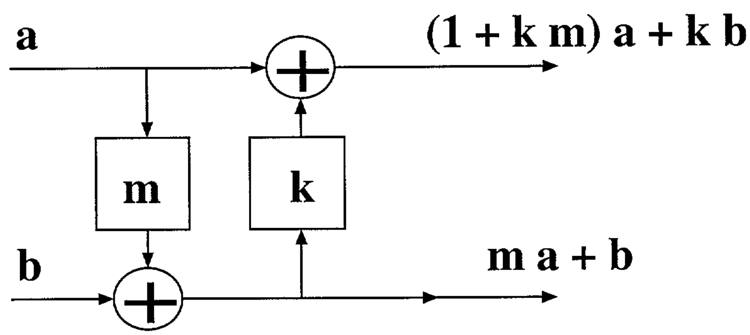

Figure 4

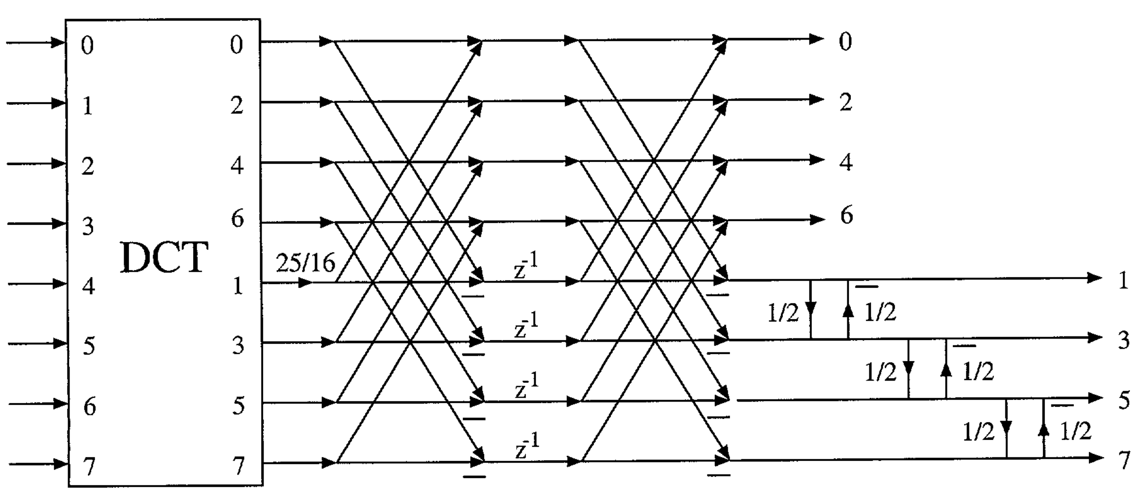

Figure 5

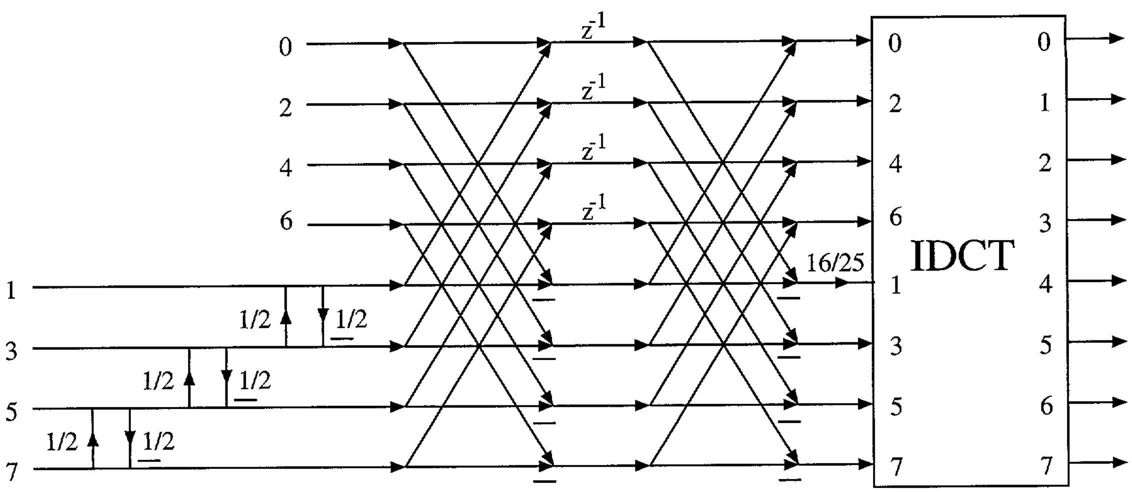

Figure 6

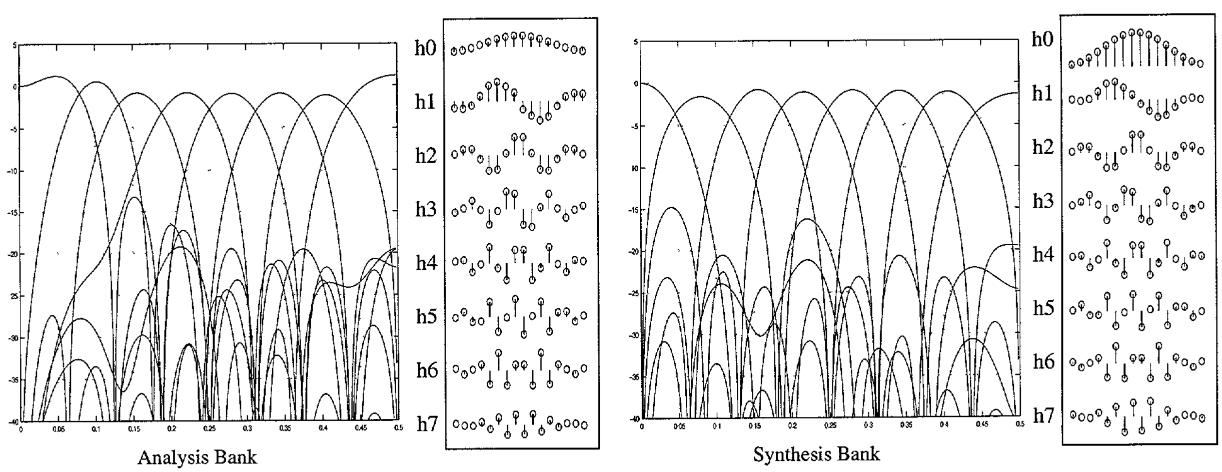

Figure 7

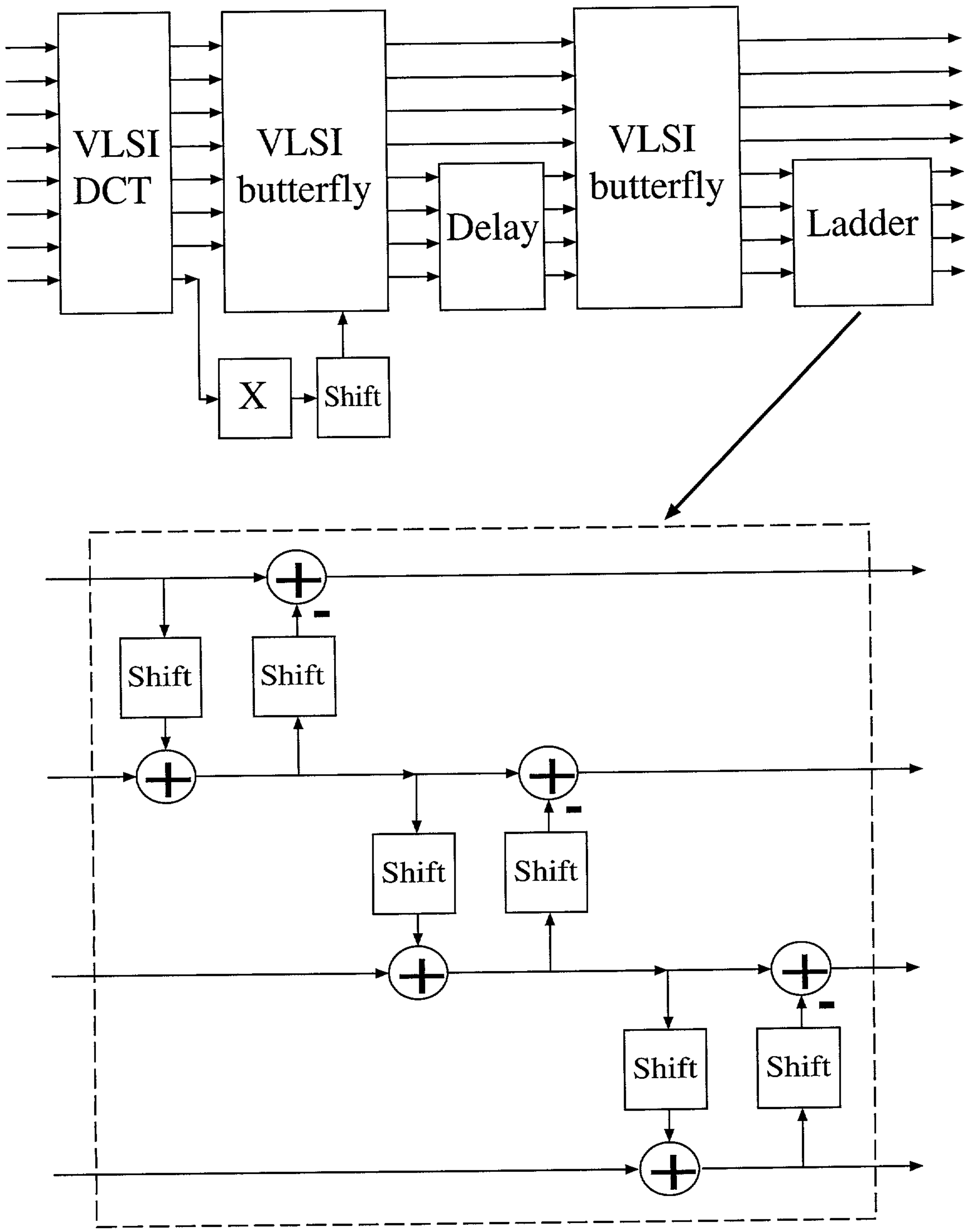
VLSI DCT
VLSI butterfly
Delay
VLSI butterfly
Ladder
X
Shift
Shift
Shift
Shift
Shift
Shift
Shift
-
-
-

Figure 8

Figure 9

PATENT APPLICATION

DECLARATION AND POWER OF ATTORNEY FOR PATENT APPLICATION	ATTORNEY DOCKET NO. 905.01

As a below named inventor, I hereby declare that:
My residence/post office address and citizenship are as stated below next to my name;
I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:
Fast Lapped Image Transforms Using Lifting Steps
the specification of which is attached hereto unless the following box is checked:

( ) was filed on _______________ as US Application Serial No. or PCT International Application Number _______________ and was amended on _______________ (if applicable).

I hereby state that I have reviewed and understood the contents of the above-identified specification, including the claims, as amended by any amendment(s) referred to above. I acknowledge the duty to disclose all information which is material to patentability as defined in 37 CFR 1.56.

Foreign Application(s) and/or Claim of Foreign Priority

I hereby claim foreign priority benefits under Title 35, United States Code Section 119 of any foreign application(s) for patent or inventor(s) certificate listed below and have also identified below any foreign application for patent or inventor(s) certificate having a filing date before that of the application on which priority is claimed:

COUNTRY	APPLICATION NUMBER	DATE FILED	PRIORITY CLAIMED UNDER 35 U.S.C. 119
			YES:____ NO:____
			YES:____ NO:____

Provisional Application

I hereby claim the benefit under Title 35, United States Code Section 119(e) of any United States provisional application(s) listed below:

APPLICATION SERIAL NUMBER	FILING DATE

U.S. Priority Claim

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code Section 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, Section 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

APPLICATION SERIAL NUMBER	FILING DATE	STATUS(patented/pending/abandoned)

POWER OF ATTORNEY:

As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) listed below to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

Frederick C. Williams, Reg. No. 36,969

Send Correspondence to: Williams & Associates 1000 Sixteenth Street, N.W. Suite 701 Washington, DC 20036-5741	Direct Telephone Calls To: (202) 842-0431 (202) 467-4045 FAX

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

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Inventor's Signature

12/13/98

Date

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Pankaj Topiwala

Inventor's Signature

12/13/98

Date